CASA Support for Polarization (Calibration)

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Context: General CASA Calibration Principles

- The Measurement Equation:

$$V_{obs} = B\ G\ D\ P\ T\ F\ V_{true}$$

- A standardized calibration model
  - Factorization of corrupting effects
  - All reduction packages have adopted some form of the above

- Hamaker, Bregman, & Sault (1995)
  - Full solution of the above is, in general, a matrix problem; *not scalar*

- Calibration is a bootstrapping process
  - General solve: $\{V_{obs}\} = J\ \{V_{mod}\}$
  - {} denotes prior calibration
  - CASA: highly modular, at least in principle

Context: General CASA Calibration Scope

- Calibration solving
  - `gaincal`: antenna-based complex gain, delay
  - `bandpass`: antenna-based channelized complex gain
  - `polcal`: antenna-based instrumental polarization, cross-hand phase
  - `blcal`: baseline-based complex gain
- Ancillary calibration: task: `gencal`
  - Antenna positions
  - Tsys (ALMA, VLBI), switched-power (JVLA)
  - Tropospheric opacity, Ionosphere (TEC)
  - Gaincurve
  - User-specified ad hoc amp, phase, or delay (antenna-, spw-, polarization-dependent)

Context: General CASA Calibration Scope (cont)

- Additional features
  - Flux density bootstrapping, including spectral fitting (`fluxscale`)
  - Plotting (`plotcal`→`plotms`)
  - Re-referencing (`rerefant`)
    - New in 5.3
    - `flex` and `strict` options
  - Flagging (`flagdata`)
  - Rudimentary time-dependent smoothing (`smoothcal`)

- Calibration application: `applycal`
  - Time- and frequency-dependent interpolation
  - Calibration fan-out (`spwmap`, etc.)
    - New: Cal Library

Cal Library

- Substitute for traditional calibration apply parameters
  - Parallel lists: `gaintable,gainfield,interp,spwmap,calwt`
  - Awkward for more than a few caltables
  - Limited calibration distribution flexibility
  - No control per MS selection → multiple `applycal` executions
- Cal Library
  - `docallib, callib`
  - File containing per-caltable calibration instructions
    - Introduces per-MS-selection specificity → single `applycal` execution
  - Also python dictionary
  - Makes OTF calibration portable to other tasks with addition of 1 parameter
  - https://casa.nrao.edu/casadocs/casa-5.4.1/reference-material/cal-library-syntax
- Adoption by ALMA pipeline pending…

Current Polarization Calibration Support

- Revised formalism:
  - Referenced (refant'd) gain calibration: $\boldsymbol{B\,G = B_r\,G_r\,X_r}$ and $\boldsymbol{D = X_r^{-1}\,D_r\,X_r}$

$$\boldsymbol{V_{obs} = B_r\,G_r\,\underline{D_r}\,\underline{X_r}\,\underline{P}\;T\,\underline{F}\;V_{true}}$$

- Instrumental polarization (channel-dependent)
  - Including $\mathcal{Q},\mathcal{U}$ solve (per spw)
  - Point-like calibrators
- Cross-hand phase (channel-dependent)
  - Artifact of *gain* calibration refant
  - NB: same as position angle for circular basis
- Parallactic angle
  - `parang=True`

- *A priori* Ionosphere (TEC) correction (low-frequency VLA)
  - `gencal: caltype='tecim'`
  - IGS TEC surface image retrieved from Goddard
  - Jason Kooi (Iowa, now NRL)
  - Limited by low spatial- and time-sampling; single pixel on line-of-sight
    - 5deg X 2deg, 2h

CASA Polarization Calibration Illustration

- From QUESO 2017 (25-27 October 2017 at ESO)
- Invited Talk: *Synthesis Polarimetry Calibration*
  - https://zenodo.org/record/1038085
- Basis-specific views

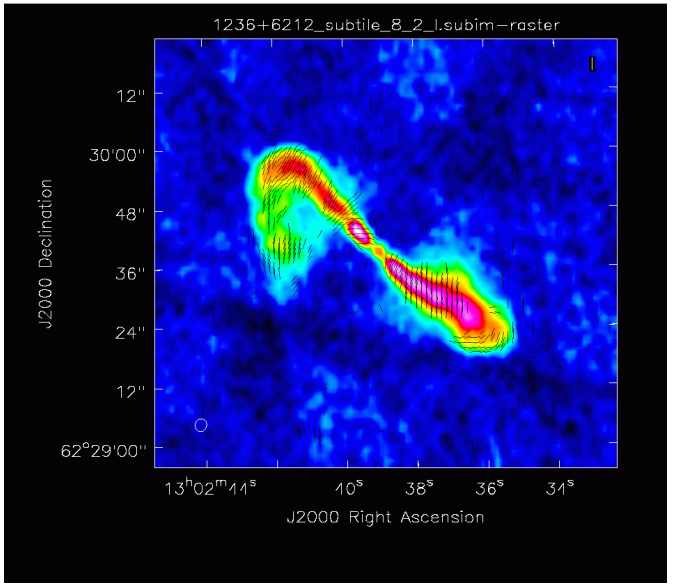
- Corresponding memo in progress…
- Updated user documentation pending

VLA: circular feed basis

- ~Traditional (VLA) heuristics:
  1. (Standard gain, bandpass calibration)
  2. Cross-hand delay: `gaincal`
     - `gaintype='KCROSS'`
     - Improve coherence for per-spw $Q,\mathcal{U}$ estimation
  3. Instrumental Polarization: `polcal`
     - General solver: `poltype='D','Df',('Dflls')`
     - Unpolarized calibrator (single scan sufficient)
     - Polarized (point-like) calibrator: `'+QU'`
       - solves for *orientation-relative* $Q,\mathcal{U}$ (multi-scan: parallactic angle coverage)
     - Relative solution
       - In cross-hand phase frame of gain refant
       - One hand on one antenna: D=0+0j
  4. Position angle: `polcal`
     - `poltype='Xf'`
     - NB: same as cross-hand phase (circular basis)

VLA: circular feed basis (cont)

- Now routinely exercised in VLASS:



- NB: EVLA instr. polarization worse than VLA
  - 5-8% instead of 1-2%
  - Stokes $\mathcal{I}$ is dynamic range limited
- NB: Relative instr. pol. solution yields impure but ~orthogonal basis
  - Good for Stokes $\mathcal{I}$, if applied to parallel-hands (and gains revised!)
    - Not yet decisively demonstrated…
  - $\mathcal{Q},\mathcal{U},\mathcal{V}$ remain dynamic range limited
    - Fatal for $\mathcal{V}$

ALMA: linear feed basis

- New (well, c.2011) heuristics (w/ `recipes/almapolhelpers.py`)
  1. (Standard gain, bandpass calibration)
  2. Cross-hand delay: `gaincal`
     - `gaintype='KCROSS'`
     - Improve coherence for per-spw $\mathcal{Q},\mathcal{U}$ estimation
  3. Time-dep gain w/ unpolarized model: `gaincal`
     - `gaintype='G'`
     - Derive $\mathcal{Q},\mathcal{U}$ estimate from **|*Gx*/*Gy*|** : `almpolhelpers:qufromgain`
  4. Cross-hand phase and $\mathcal{Q},\mathcal{U}$ estimation from cross-hands: `gaincal`
     - Adequate parallactic angle coverage
     - Significantly polarized calibrator (no known unpolarized point-like calibrators)
     - `gaintype='XYf+QU'`
     - Resolve 180 deg ambiguity: `almapolhelpers:xyamb` (using qufromgain result)
  5. Revise time-dep gain w/ polarized model
  6. Instrumental polarization: `polcal`
     - Significantly polarized calibrator
     - `poltype='Dflls'`

ALMA: linear feed basis

- NB: An "absolute" instrumental polarization calibration
  - relative to estimated $\mathcal{Q},\mathcal{U}$
  - Symmetrized orientation
  - Stokes $\mathcal{V}$ and net instrumental ellipticity degenerate
- NB: ALMA non-standard: Manual processing on standard pipeline results
  - Manually-concatenated execblocks
  - Encouraging single-execblock executions for polarization in Cycle 7

Polarization Calibration Development (CASA 5.5)

- Optimize/modularize features for pipeline deployment
- Standardize user-facing polarization calibration semantics in ~basis-independent way, as much as possible

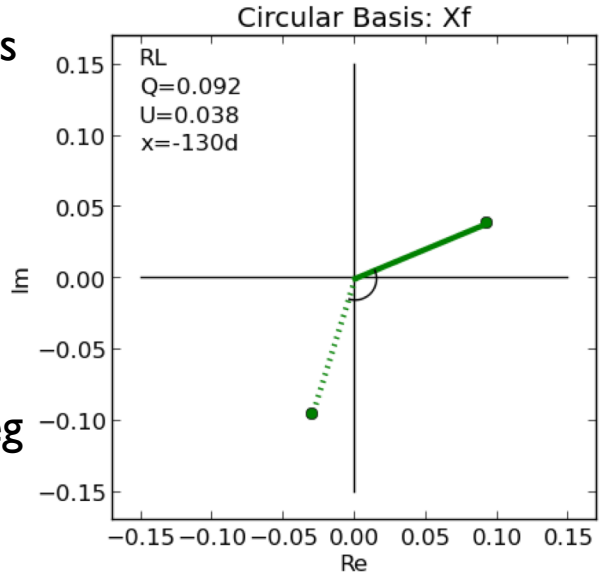
1. Move critical almapolhelpers-based functions into tasks
   - QU estimation from gain amp ratios (replaces qufromgain)
     - `gaintype='G+QU'` (linear basis only)
   - Automate cross-hand phase 180d ambiguity resolution (replaces xyamb)
     - Relies on Q,U determined above, and supplied as prior

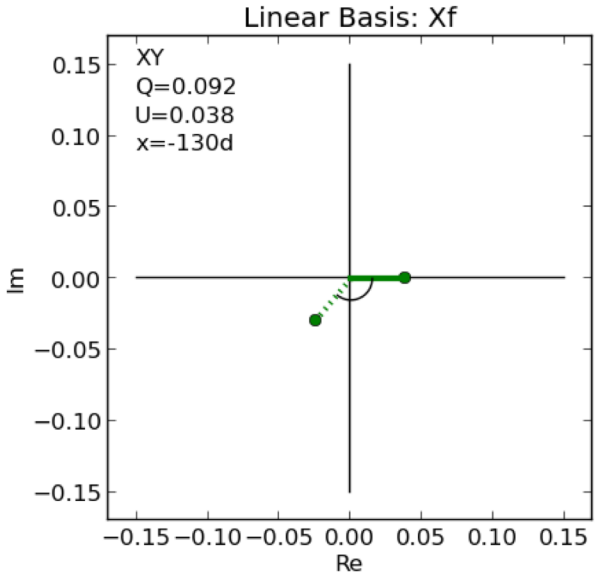
Polarization Calibration Development (CASA 5.5)

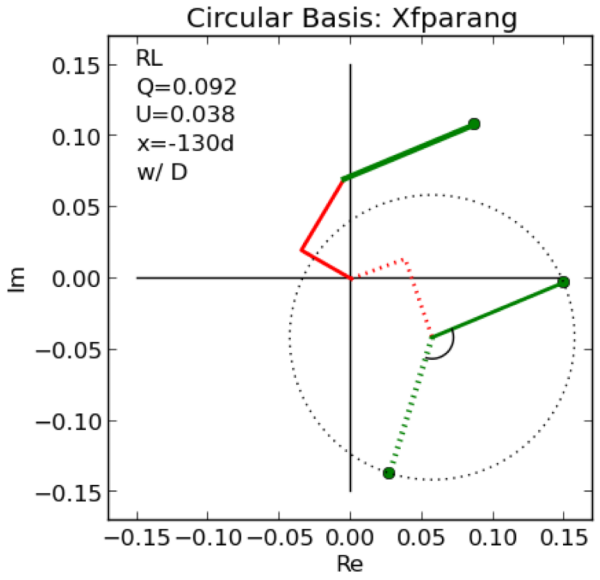
2. Modularization of cross-hand phase and QU solving within `polcal`
   - `poltype='Xfparang'`
     - Instrumental polarization-agnostic cross-hand phase solve (requires parallactic angle coverage)
     - Permits general cross-hand phase registration prior to $\mathcal{Q},\mathcal{U}$ and instrumental polarization solve
     - Linear basis: migrated from `gaintype='XYf+QU'` (complex slope)
       - Including ambiguity resolution
     - Circular basis: migrated from `poltype='D+X'` (offset center)
   - Modularize and improve basis-specific cross-hand $\mathcal{Q},\mathcal{U}$ solvers for basis-agnostic use prior to instrumental polarization solve
     - Requires parallactic angle coverage
   - Add explicit position angle solution: poltype='PA'
     - Circular basis: same as simple cross-hand phase (`'Xf'`), but with external model
     - Linear basis: explicit orientation registration (*not* cross-hand phase!)
       - So far, have relied on known mechanical registration

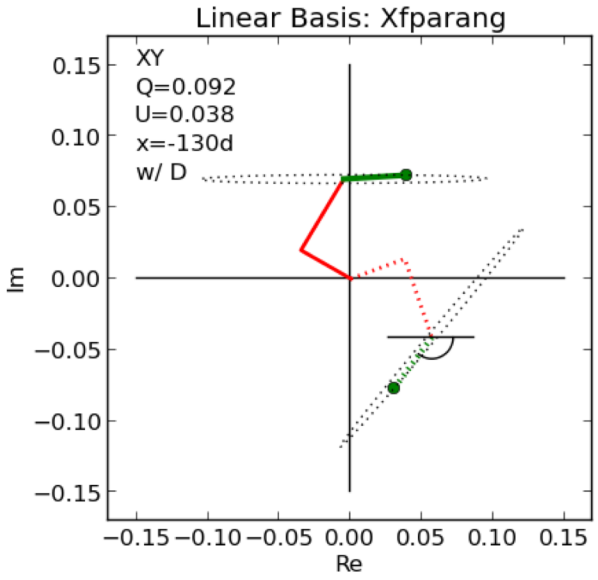
Cross-hand phase solutions

- Gain-calibrated crosshands in the complex plane
  - at transit
- Nominally:
  - $RL = \mathcal{Q} + i\mathcal{U}$
  - $XY = \mathcal{U} + i\mathcal{V}$
- Crosshand phase=-130 deg
- Instrumental polarization causes offset of $\mathcal{Q}=\mathcal{U}=0$ response from origin
- 'Xfparang' leverages parallactic angle-driven evolution of response
  - Circular basis: offset center
  - Linear basis: slope
    - Note 180 deg ambiguity
- Stokes $\mathcal{V}=0$!
  - Instrumental polarization solution absorbs it…









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Standardized Polarization Calibration Heuristics

- ~Basis-agnostic semantics:
  1. (~Standard gain, bandpass calibration)
  2. Time-dep gain w/ unpolarized model: `gaincal`
     - Linear basis: $\mathcal{Q},\mathcal{U}$ estimated, removed
  3. Cross-hand phase registration: `polcal`
     - `poltype='Xfparang'`
     - Linear basis: ambiguity resolution included
  4. Estimate $\mathcal{Q},\mathcal{U}$ from cross-hands: `polcal`
     - `poltype='QU'`
  5. Instrumental polarization: `polcal`
     - `poltype='Dflls'`
  6. Revise gain/bandpass calibration using full-polarization model, if necessary
     - Generalized selfcal

- Ad hoc scenarios also flexibly supported
  - E.g. time-dependent cross-hand phase (`poltype='Xf'`) at 5a
  - Limited parallactic angle and standard calibrators (*a priori* $\mathcal{Q},\mathcal{U}$)

Topics Under Continuing Study

- Direction-dependent instrumental polarization (ARDG)
- Refine full non-linear instrumental polarization solution?
  - Study in collaboration with Seiji Kameno (JAO)
  - As yet unclear if sufficient leverage practically available
- Polarization calibration iteration
  - Generalized self-cal
- Generalized aggregate (statistical) refant
  - Avoid availability problems (time, spw)
- Stokes $\mathcal{V}$: Need to calibrate the zero point
  - No absolute external reference available at required *accuracy* (<<0.1% of $\mathcal{I}$)
  - Zeeman: Detect spectral signature (not yet working reliably at ALMA)
  - Continuum: Statistical constraint: Universe has no preferential handedness (e.g., ATCA: Rayner et al., 2000)
- Observatory-provided instrumental polarization?
  - Appears stable over months+
  - Requires adequate sampling in frequency, updates upon RX 'events'
  - Adapted heuristics for cross-hand phase calibration (non-parallactic angle coverage case)
- ALMA: "artificial source" : detailed heuristics TBD
- Resolved calibrators? (VLBI)
  - `'Xfparang'` in this context?

Polarization Analysis

- Stokes Visibility plotting expected in `plotms` in 5.5?
- Image math: `immath`
  - Position angle: `mode='pola'`
  - Polarized intensity: `mode='poli'`
    - Including bias correction
  - Masks supported

- RM Synthesis: not currently supported